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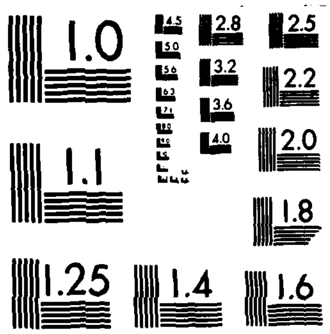

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MAGNETOMECHANICAL PROPERTIES OF FLASH ANNEALED METGLAS® 2605 SC

BY M. WUN-FOGLE, L. T. KABACOFF

RESEARCH AND TECHNOLOGY DEPARTMENT

5 OCTOBER 1984

NAVAL SURFACE WEAPONS CENTER

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Ribbons of METGLAS® 2605 SC were flash annealed at various temperatures and under various tensile stresses. The resulting samples exhibited a magnetomechanical coupling, K_{33}, of 0.37, independent of the annealing temperature or the magnitude of the stress. Secondary annealing in a strong magnetic field greatly improved the value of K_{33}. As quenched ribbons subjected to the same field, annealing had significantly smaller values of K_{33}, except for relatively long anneals (greater than 2 hours at

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300 °C). Secondary annealing in a small magnetic field produced a much smaller increase in K_{33}. Originator supplied keywords include:

FOREWORD

In this report, the question of how to achieve improved ductility in magnetostrictive transducer materials without sacrificing transducer properties is examined. The approach is to examine the effect of short term high temperature preannealing (flash annealing) followed by relatively low temperature conventional magnetic annealing on the magnetomechanical properties of metallic glass ribbons. The results and conclusions presented here should be of value to scientists and engineers who are involved in designing sensors or transducers.

This work was performed for and funded by the RST Acoustic Sensor Materials Project under STP 4211 rapid solidification task WF-61-452 administered by Dr. G. J. London, NADC, Warminster, PA 18974. It is part of an ongoing program to develop magnetostrictive transducers with very high magnetomechanical coupling factors. The authors wish to thank Dr. T. Jagielinski and Dr. H. T. Savage for many invaluable comments and suggestions, and Dr. T. Jagielinski for his help in producing flash annealed ribbons.

Approved by:

Jack R. Dixon

JACK R. DIXON, Head
Materials Division

CONTENTS

ILLUSTRATIONS

TABLES

CHAPTER 1

INTRODUCTION

Many ferromagnetic metallic glasses, when properly annealed in a saturating magnetic field, exhibit a giant ΔE effect and a very large magnetomechanical coupling factor, K_{33}.[1] The highest value of K_{33} observed thus far is 0.92 for METGLAS®* 2605 SC.[2] The magnetic annealing process accomplishes two things: (1) relief of inhomogeneous stresses quenched into the material during meltspinning and (2) the establishment of a small uniaxial anisotropy with easy axis lying in the plane of the ribbon transverse to its length. Structural relaxation also occurs during annealing. The effect of this structural relaxation on K_{33} has not been examined. Since structural relaxation makes the ribbons brittle, it would be very useful to have a technique for producing ribbons with high magnetomechanical coupling which does not permit structural relaxation to occur.

Recent reports indicate that stress relief may be accomplished by the process of "flash annealing" in which ribbons are heated to high temperature very rapidly and then cooled very rapidly.[3,4] This treatment does not result in any structural relaxation, as indicated by the fact that the Curie temperature is unaffected.[3] Uniaxial anisotropy may be introduced in a number of ways, such as annealing under stress, or by low temperature annealing. Thus, the possibility exists that a magnetostrictive transducer material with relatively high K_{33} and reduced brittleness might be achievable.

In this report we give details of measurements of the magnetomechanical properties of METGLAS® 2605 SC ribbons which were flash annealed in air under various tensile stresses. The effect of subsequent low temperature annealing is also discussed.

*METGLAS® is a registered trademark of Allied Chemical Corporation.

CHAPTER 2

EXPERIMENTAL

FLASH ANNEALING

A first group of METGLAS® 2605 SC amorphous ribbons were cut into 2 x 1/16 x.001-inch strips and flash annealed in air by subjecting the sample to an electric current that passes directly through the material. Typical heating time was 0.35 to 0.50 seconds. Typical cooling time was 3 seconds. The final temperature achieved was estimated by monitoring the voltage in a pickup coil surrounding the ribbon while subjecting the coil to a small AC magnetic field. Figure 1 shows a typical curve of the voltage in the pickup coil versus time. By noting the time the voltage goes to zero and the total length of the current pulse, and assuming a constant heating rate, the final temperatures were estimated. It was difficult to maintain the same flash annealing temperature from sample to sample. Final flash annealing temperatures varied between 403 and 611°C. During annealing, the ribbons were subjected to various tensile stresses by hanging small weights (0 - 100 gm) from one end of the ribbon.

Flash annealed ribbons were next conventionally annealed at 220°C for various periods of time up to 2 hours. Some were annealed in a strong magnetic field (5 KOe), while others were annealed with the magnet power supply turned off (the residual field was 22 Oe).

A second group of ribbons (3" x 1/16" x .001") were similarly flash annealed, characterized, and conventionally annealed at 300°C for various times up to 2 hours. The change in ribbon length was made because it was observed that the demagnetizing field in the 2-inch ribbons was not negligible.

MAGNETOMECHANICAL PROPERTIES

The magnetomechanical coupling factor, K_{33}, was measured for each sample by a resonance technique. Samples were placed in a pickup coil and subjected to a bias field, H_b, and a small AC drive field. With H_b held constant, the frequency of the drive field was swept, and the resonance and antiresonance frequencies determined by the maxima and minima in the pickup voltage. The value of K_{33} was calculated from the equation:

$$K_{33}^2 = (\pi^2/8)\left(1 - \frac{f_r^2}{f_a^2}\right) \qquad (1)$$

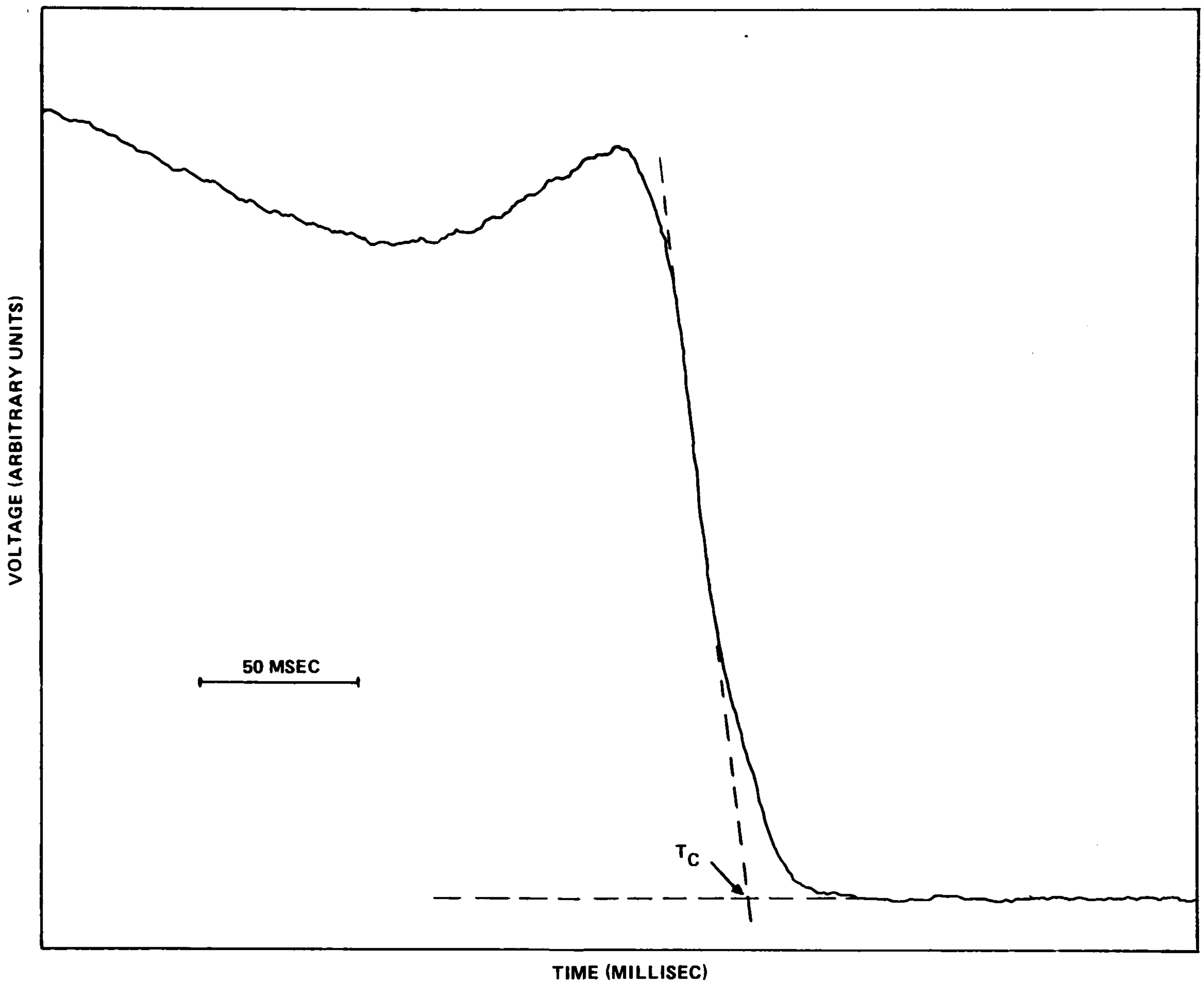

FIGURE 1. PICKUP COIL VOLTAGE DURING FLASH ANNEALING AS A FUNCTION OF TIME
(The beginning and end of the pulse are marked by a transient voltage spike (not shown).)

where f_r and f_a are the resonance and antiresonance frequencies, respectively. The anisotropy field, H_a, was determined from the bias field which gave the minimum in the plot of resonance frequency versus H_b.

DUCTILITY MEASUREMENTS

Ductility measurements were performed on as quenched ribbons, flash annealed ribbons and on ribbons which were flash annealed and subsequently reannealed at 220 or 300°C. This was done by placing a ribbon bent into a "U" shape between the jaws of a vernier caliper and noting the separation of the jaws at the moment of failure.

CHAPTER 3

RESULTS AND DISCUSSION

The value of K_{33} for flash annealed 2-inch ribbons was suprisingly unaffected by flash annealing temperature for temperatures between 403 and 566°C or tensile stress. For all samples flash annealed below 600°C, the magneto-mechanical coupling factor was 0.37 ± 0.01; by comparison, $0.22 < K_{33} < 0.27$ in as quenched ribbons. Above a flash annealing temperature of 600°C the ribbons were clearly crystalline. All uncrystallized samples showed complete 180° bend ductility.

Examination of the plots of resonance frequency versus bias field shows that the samples fall into two groups, as illustrated in Figure 2. Ribbons flash annealed below 500°C exhibit curves which have a deeper, better defined minimum. The ribbons flash annealed above 500°C showed broader, more shallow curves. Broadening usually indicates a wide variation in the local direction of the easy axis, probably due to small amounts of microcrystallinity. Even for ribbons flash annealed below 500°C, the minima in f_r are broader than that which is found in conventionally annealed ribbons with high K_{33}. Also, the value of H_b corresponding to a minimum f_r, even when corrected for demagnetizing field, is about twice as large as is found in the conventionally annealed ribbons. It appears that the anisotropy formed during flash annealing under stress is too large for high coupling, and has a great local variability.

The results of flash annealing followed by conventional annealing at 220°C is summarized in Table 1, together with the results of annealing as quenched ribbons at 220°C. Annealing in the small residual magnetic field produced no change in the value of K_{33}. However, when annealed in a strong magnetic field, the value of K_{33} increased significantly, up to 0.46.

The effect of secondary annealing of flash annealed samples at 300°C is summarized in Table 2. The effect of 300°C annealing on as quenched ribbons is also shown. As may be seen from the table, there is a substantial difference between the results for flash annealed and as quenched samples for annealing in both a 5 KOe and 22 Oe field. In the case of low field annealing, the higher values of K_{33} in the flash annealed ribbons persist after 2 hours of annealing (0.52 versus 0.39 for flash annealed and as quenched, respectively). In the case of 5 KOe annealing, the difference in K_{33} between flash annealed and as quenched ribbons nearly disappears after 2 hours of secondary annealing (0.73 versus 0.75 for as quenched and flash annealed samples, respectively). However, for annealing times of 1 hour or less, the flash annealed ribbons exhibit much higher coupling.

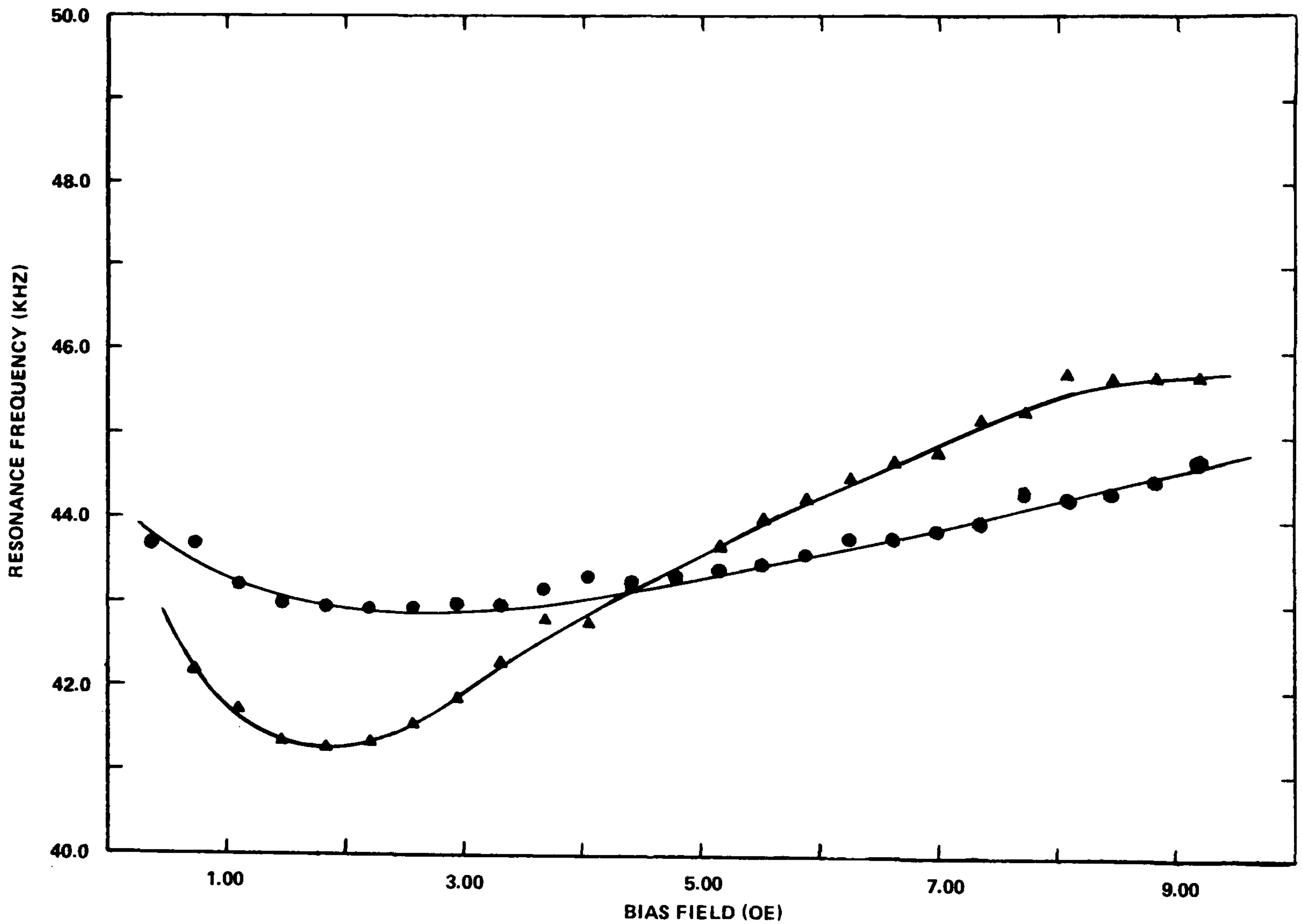

FIGURE 2. TYPICAL PLOTS OF RESONANCE FREQUENCY VERSUS BIAS FIELD FOR 2-INCH RIBBONS FLASH ANNEALED TO A FINAL TEMPERATURE ABOVE (●) AND BELOW (▲) 500°C

TABLE 1. MAGNETOMECHANICAL COUPLING FACTOR OF 2-INCH FLASH ANNEALED (F. A.)* AND AS QUENCHED (A. Q.) RIBBONS FOLLOWING 220°C SECONDARY ANNEALING

ANNEALING HISTORY	SECONDARY ANNEALING TIME (MINUTES)			
	0	30	60	120
A. Q. + High Field (5 KOe)	--	0.41	0.43	0.44
A. Q. + Low Field (22 Oe)	--	0.36	0.37	0.37
F. A. + High Field (5 KOe)	0.37	0.45	0.46	0.46
F. A. + Low Field (22 Oe)	0.38	0.39	0.39	0.39

*Flash annealing temperature was 448 ± 5°C.

TABLE 2. MAGNETOMECHANICAL COUPLING FACTOR OF 3-INCH FLASH ANNEALED (F. A.)* AND AS QUENCHED (A. Q.) RIBBONS FOLLOWING 300°C SECONDARY ANNEALING

ANNEALING HISTORY	SECONDARY ANNEALING TIME (MINUTES)			
	0	30	60	120
A. Q. + High Field (5 KOe)	0.27	--	0.55	0.73
A. Q. + Low Field (22 Oe)	0.27	0.35	0.38	0.39
F. A. + High Field (5 KOe)	0.38	0.60	0.72	0.75
F. A. + Low Field (22 Oe)	0.38	0.52	0.55	0.52

*Flash annealing temperature was 397 ± 5°C.

All ribbons annealed for 220°C for 2 hours exhibited perfect 180° bend ductility (caliper jaw separation of 0.003-inch). Ribbons annealed for 2 hours at 300°C failed at a caliper jaw separation of 0.005-inch. By comparison, ribbons annealed at 380°C for 10 minutes failed at a jaw separation of 0.038-inch. The results obtained depended very strongly on the strain rate. For the more brittle samples, there was a great deal of scatter due to surface defects and variation in ribbon thickness. The numbers reported are therefore the minimum values obtained from a large number of trials and for very low strain rates.

It is clear from the results presented above that flash annealing by itself does not produce high values of K_{33}. This appears to be because the transverse anisotropy thus formed is too large and insufficiently uniform in direction throughout the sample. Secondary annealing in a magnetic field improves the coupling. For a given annealing temperature, the annealing time required to maximize the value of K_{33} is considerably shorter in flash annealed ribbons than in as quenched samples. This is a welcome result since shorter annealing times mean less embrittlement.

CHAPTER 4

CONCLUSIONS

In this study we have achieved a coupling of 0.72 with high ductility in METGLAS® 2605 SC by means of flash annealing followed by a 60 minute, 300°C secondary magnetic annealing. Longer secondary annealing of the metallic glass ribbon produces slightly higher coupling with a loss of ductility.

It is evident that the secondary annealing improves the uniformity of the transverse anisotropy. It would be better, however, not to have to overcome the lack of uniformity introduced during the flash annealing. Two ways in which this might be accomplished are to flash anneal in a strong longitudinal magnetic field so that all of the transverse easy axis is produced by the secondary anneal, or to flash anneal in a very strong transverse field with very little applied tensile stress, so that the anisotropy thus produced will (hopefully) be more uniform. These experiments are in progress as is an extension of the current work to higher secondary annealing temperatures.

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